Master Thesis

Yoren Schriever

I have chosen to write my master thesis in the form of a grant proposal for PhD research. I am applying for a grand in the free competition from NWO. The structure of my proposal will be according to the guidelines of the NWO. More information can be found on: http://www.nwo.nl/nwohome.nsf/pages/NWOP_5U2LBW

1a Project title

A neurological motivated computational model for beat induction

1b Project acronym

None

1c Principal investigator

Yoren Schriever

1d Renewed application

This is a new application

2a Scientific summary. Max. 250 words

Current models for beat induction give an accurate description of the phenomenon. These models however have their emphasis on recreating behavioural aspects; lacking an explicit neural correlate. Finding this neural correlate is one of the current challenges in the field of music cognition. In this research proposal the Fitzhugh-Nagumo model is taken as a starting point for a model for beat induction. This model is able to synchronize phase at equal tempi of the internal oscillator and external input, however it lacks the potential to synchronize to other tempi.

In two experiments we will measure whether the influence of perturbations in the external input signal is dependent of the metric position of that perturbation. The literature suggests that perturbations close to a beat have higher influence that those further away. Also a slight asymmetry is expected for “too early” and “too late” onsets. One experiment will focus on the influence on the conscious perception, the other on synchronization of finger movement.

Using these experiments, and using existing literature, a subdivision is made between the unconscious synchronization of body movement, phase synchronization and the cerebellum on one hand and conscious perception of asynchrony, period (tempo) adjustment and the prefrontal cortex on the other hand. Relations within these groups suggest a model in which phase synchronization take place subconsciously in the cerebellum, under control of other brain areas to adjust the tempo of the internal timekeeper. The result of this project will be a model for beat induction that describes a neural process.

2b Abstract for laymen (in Dutch). Max. 500 words

Beat inductie is een van de onderzoeksonderwerpen binnen de muziek cognitie. Het is het proces dat, bij het horen van een externe, ritmische input een onderliggende isochrone beat kan extraheren en lichaamsbeweging hieraan kan synchroniseren. Het maakt samen dansen en muziek maken mogelijk en wordt gezien als een basismechanisme in de evolutie van muziek. Huidige modellen voor beat inductie zijn abstracte, statistische en/of ingenieursmodellen. Sommige daarvan geven weliswaar een accurate beschrijving van het fenomeen, over een neurale analogie van de modellen wordt weinig gesproken. In dit onderzoeksvoorstel wordt het Fitzhugh-Nagumo oscillator model, een beproefde mathematische beschrijving van een aantal gekoppelde neuronen, als uitgangpunt genomen voor een model voor beat inductie. Dit model bevat de eigenschappen om bij gelijke tempi de fase te synchroniseren van de interne oscillator aan de muziek, maar het ontbreekt dit model nog om te kunnen synchroniseren aan een ander tempo. In twee experimenten zal worden gemeten of de invloed van perturbaties van het externe input signaal van grotere invloed is op punten waar een beat verwacht wordt dan op plekken waar deze niet verwacht wordt. Eén experiment zal zich toespitsen op de bewuste waarneming van een dergelijke verstoring, het tweede experiment richt zich op de synchronisatie van vingerbeweging aan de verstoring, ongeacht deze wordt opgemerkt.

Met behulp van deze experimenten en voorbeelden uit de literatuur wordt er onderscheid gemaakt, overeenkomstengezocht en verbanden gelegd tussen onbewuste synchronisatie van lichaamsbeweging, fase synchronisatie en het cerebellum (een hersengebied geassocieerd met het onderbewuste en bewegingsplanning) enerzijds, en bewust opgemerkte asynchroniteit, periode (tempo) aanpassing en andere gebieden in de cerebrale cortex anderzijds. Onderlinge verbanden binnen deze twee groepen suggereren een model waarin fase synchronisatie onbewust plaatsvindt in het cerebellum, onder invloed van deze andere gebieden die het tempo kunnen bijsturen. Aan de hand van het opgestelde neurale model voor beat inductie zullen een aantal voorspellingen worden gedaan die vervolgens op proefpersonen getoetst worden met fMRI en TMS, welke de werking van bepaalde hersengebieden tijdelijk van verstoren. Het resultaat van dit onderzoek is het eerste model voor beat inductie met een neuraal analogon.

2c Keywords (max. 6)

Beat induction, Model, Neural Correlate, Fitzhugh Nagumo, Oscillator, Sensory Motor Synchronization

3 Classification

Music Cognition

4 Composition research team

Schriever	Y.	MSc	PhD Candidate
Honing	H.	Prof. Dr.	Promotor

5 Research school

Institute for Logic, Language and Computation (ILLC)
University of Amsterdam, P.O. Box 94242, 1090 GE Amsterdam, The Netherlands

6a Description proposed research

Beat induction the is ability to extract an isochronous timed signal (beat) from a piece of music, even if the beat is not explicitly present. It is essential when playing along with the drummer in a band, or when dancing to music and hence considered fundamental to music and music making. It is argued to have played an essential role in the evolution of music. Beat induction covers not only the synchronization of movement to music but also the conscious awareness of such a beat. (Honing et al., 2009; Patel, 2008)

Numerous attempts have been made to model the phenomenon of beat induction. (Michon, 1967; Drake & Botte, 1993; Povel, 1981 and Large & Jones, 1999). Only few of these numerous articles say something meaningful about the neural implementation of beat induction or the brain regions are involved in this process. Most models are abstract, statistical or engineer models, making them suitable for use on a computer, but having little to no neural correlate.

Regarding neural behaviour in general and not beat induction in particular, Hodgkin and Huxley described a model for the dynamic properties of action potentials (Hodgkin & Huxley, 1952). Later, this model was simplified by Fitzhugh and Nagumo (Fitzhugh, 1961; Nagumo et al., 1962), resulting in a set of equations that is still used to model the spiking behaviour of neurons (Izhikevich, 2004)

In this proposal, we zoom in on one particular model that gives an accurate description of the behavioural phenomena of beat induction: The one constructed by Large & Jones (1999) and mathematically deeper discussed by Large & Kolen (1994). The basis for this model also arose from Fitzhugh and Nagumo's equations, which were altered in several ways in order to construct a model to track the attentional focus of a listener. It is a model based on Jones' theory of periodic modulated attention. This theory states that listeners are more sensitive to onset deviations close to beats than to deviations in between beats. i.e. The attention is focussed around the beats. This model can be used to predict the relative attention at a certain point (phase) in the internal cycle.

When constructing their model a set of assumptions and mathematical simplifications were made, losing the neural analogy of the Fitzhugh Nagumo model:

1) When making the simplification to their so called canonical model, the nuances of the neural properties are nullified. Simplifying the phase space diagram to a circle.
2) The sinusoidal attractor of the limit cycle is replaced by an arbitrarily chosen attentional pulse curve (parameterized by kappa or gamma in their publications)
3) Period correction is introduced by re-using the mathematical structure of phase correction. The problem here is that phase correction is an intrinsic physical property of oscillators and period adjustment is not. The internal period of an oscillator is only dependent on its own physical properties, not on coupling. Since these processes do not have the same origin, there is no reason to assume a common mathematical structure.

The model has become an engineer model that can adjust tempo and phase instantaneously with a magnitude that needs to be computed mathematically, instead of a model describing neuronal interaction in a mathematical fashion. Furthermore, the model of Large and Jones is written from the point of view of attention, not for predicting the onset of the next beat.

Phase I: Experiments

The model we aim to construct differs on two major points from Large & Jones': It will be a model with the original intention to model position of the next tap instead of attention and, most important, it will be a model that is plausible in the context of neural implementation. Eck (2002) proved that the simple network of Hodgkin Huxley cells that formed the mathematical starting point for Large and Jones was also capable of beat induction by itself. Using simulations he showed that this model can find the downbeat in complex rhythmic input signals and synchronize itself to it. The big advantage of this network is that is a direct application of the Fitzhugh-Nagumo equations, meaning that is has a neural analogy. Some disadvantages of this model are that it has difficulties synchronizing to some syncopated rhythms (rhythms containing silence where a beat is expected), and that it ignored continuation phase behavior - i.e. Continuation in the same tempo when the external input is removed. This in contrast to behavioural data (Semjen et al., 2000). The first problem might be reduced by using a network of coupled oscillators, making its behavior more stable and less sensitive to syncopation. Note that also in humans this sensitivity to syncopation is present to a certain extend (Patel et al., 2005). Because of the neural analogy, the model of Eck is a good foundation to build our new, neurally realistic model for beat induction.

The model of Large & Jones predicts that there is more attentional focus around the positions of the beats compared to inter-beat locations. Eck's model predicts something similar, namely that input pulses close to a beat generate relatively more intense phase adjustment towards that beat than pulses further away from a beat. Both predictions are mathematically similar, but there is a difference in approach. One of the differences between the two models is that Eck's model predicts that early onsets are more salient than late onsets when adjusting the internal phase. In Large & Jones this asymmetry is not present. To test these predictions, we propose two experiments. Both experiments use psychophysics, measuring the possible presence of attentional focus in conscious perception. The second experiment is a tapping experiment, directly measuring the tap-predicting behavior of the internal oscillator when being fed inconsistent input.

Experiment 1: Attentional focus on and in between beats

As stated above, the Large & Jones' model predicts that listeners are less sensitive to deviations in onsets when these onsets are further away from a beat. Close to a beat the model is most sensitive, and relatively large adjustments will be made to the internal phase, but as the input pulse falls further away from the expected position, it will be less treated as a "too-early" or "too-late" beat, and more seen as a pulse at a different metric position. So: the further away from a beat, the smaller the adjustment.

Experimental paradigm:

In each trial, subjects will be confronted with a musical context that will set their internal time keeper (priming). This context contains a clear metric hierarchy of two levels. After a few repetitions of the context, the target will follow, consisting of a constant number of bars where all onsets are replaced by monotonous beeps with equal intensity. This is done in order to have targets that have the same physical structure, independent of the context metre. The monotonous beeps will be perceived as having the same metric structure as the context however (Jongsma et al., 2004). One of the target onsets will be adjusted by a slight interval delta t. The task for the subject is to indicate whether he noticed the interval adjustment for different values of *delta t* - A simple signal detection paradigm. This will be done at different (perceived) metric positions of the monotonous target. Three types of context will be used. A context with a 2/4 metre, containing onsets in the scheme: strong, weak, strong, weak, a context with a ¾ metre, having strong, weak, weak, strong, weak, weak as rhythmical structure and a context with a 4/4 metre with a strong, weak, weak, weak structure. See fig. 1. Using these three contexts, the attentional sensitivity can be measured at 6 phase positions: phase 0: the strong metric pulse in all contexts. Phase 1/3: the first weak pulse in the ¾ context. Phase ½: the weak pulse in the 2/4 context, and phase 2/3 which is measured at the second weak pulse in the ¾ metre context. In the 4/4 context, the attentional sensitivity at ¼ and ¾ can be measured.

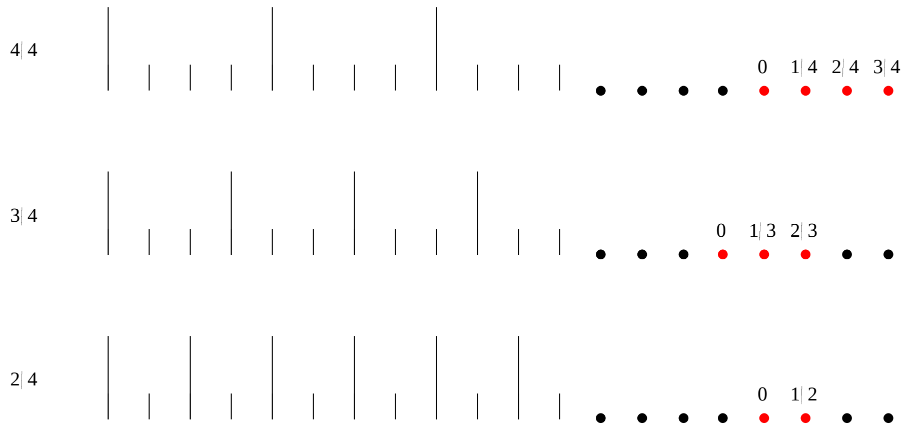

Fig 1. Experimental paradigm for experiment 1. High bars represent strong onsets, Low bars weak. Dots are monotonous beeps of equal intensity. Red dots represent target beeps. For each trial, one of the three metres is chosen and its context is played. After several repetitions the context ceases and is followed by a set of beeps. For each trial the position of only one of the target beats is slightly adjusted. Subjects have to indicate whether they noticed the onset adjustment. Using a staircase method the threshold can be found for each metric position.

Possible outcomes of this experiment might be:

1) No modulation: Participants are equally sensitive to all metric positions
2) Symmetric modulation: Participants are most sensitive on a beat, and least sensitive in-between beats. On the 1/3 and 2/3 (as well as ¼ and ¾) phase positions the sensitivity is equal.
3) Asymmetric modulation: Participants are most sensitive on a beat, and least sensitive in-between beats. On the 1/3 and 2/3 (or ¼ and ¾) phase positions the sensitivity is not equal. I.e. the participants were more sensitive on early or late positions.

Literature (McAuley, 1995) suggests outcome 3. In Large & Jones (1999) this asymmetry is not present, but it could easily be implemented. Jongsma et al. (2004) did a similar experiment, and also measured the p3a signal (associated with expectancy, which is not directly attention). Their behavioural as well as their EEG results supported the hypothesis for modulated attentional focus for musically trained participants. For untrained participants this hypothesis was not supported. Possible asymmetry in the attentional curve was discussed.

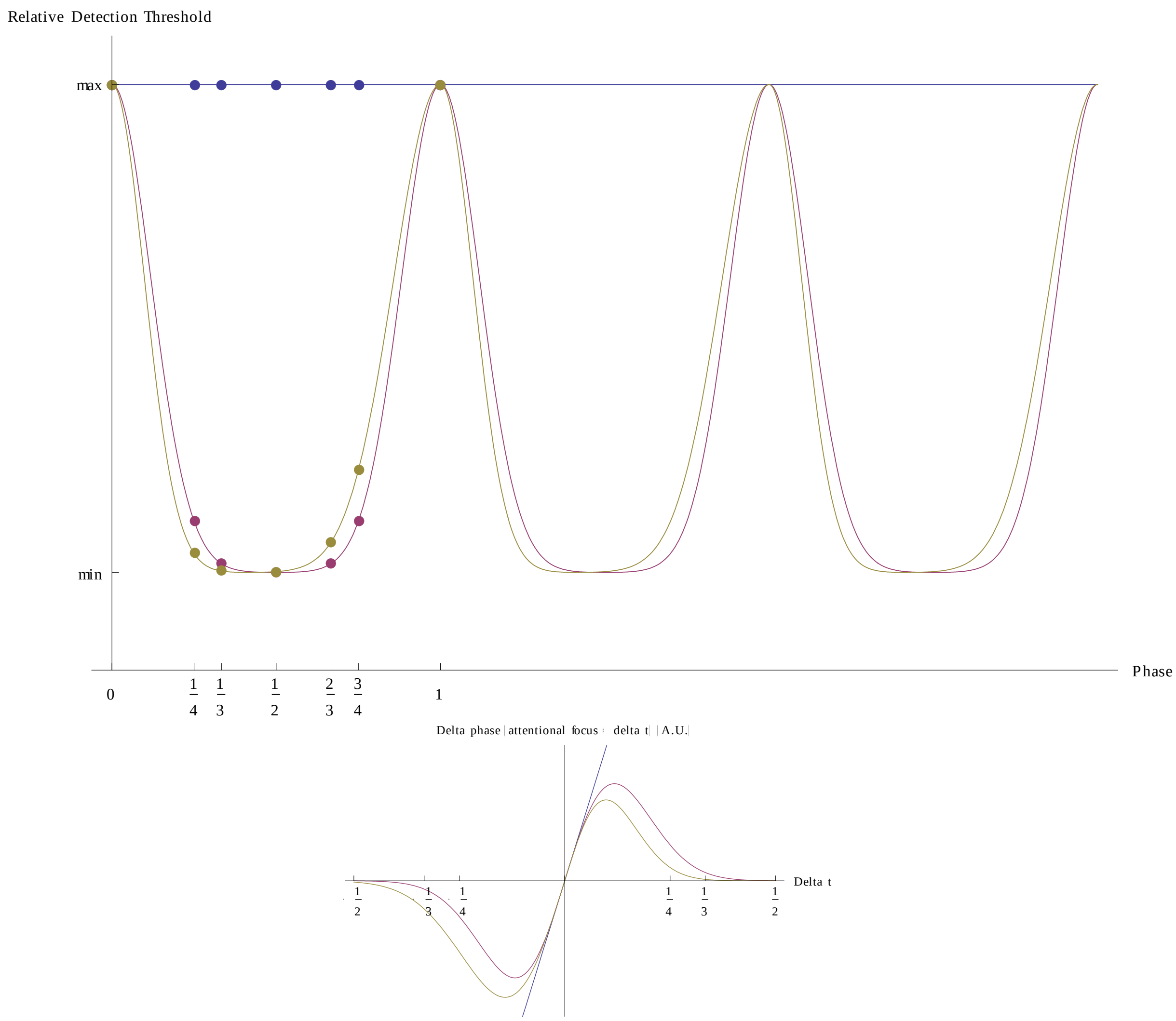

Fig 2 TOP: Attentional focus expressed as relative detection threshold over time. The lines represent the theoretical curves of the three possible outcomes. (Blue=constant, red=symmetric, yellow=asymmetric) The dots are the only points that can be measured. BOTTOM: Amount of phase adjustment predicted by Large & Jones' model for the three outcomes on in the left illustration. This graph is constructed by multiplying the detection threshold, - a measure for attentional focus - by the value of delta t, and can be used to compare the outcomes to that of experiment 2.

When introducing the hierarchic context, we implicitly assumed the suggestion of Large and Jones that participants do not contain one beat induction module, but multiple. Each of them being able to lock to a certain hierarchic level of the meter. Some of these modules will lock to the lowest level of hierarchy, predicting maximum attention at all pulses, and some of them will lock to the highest level, only predicting maximum attention at strong pulses. This is also the reason why we do not expect the participants to be completely insensitive at phase ½. Although the model at the highest hierarchical metrical levels predicts this, the model at the lowest level predicts maximum attention. The measured attention will be a mixture of both hierarchies, so it will never reach zero.

If the phase ¼, 1/3, ½, 2/3 and ¾ sensitivities are equal, we have to keep in mind that this is not proof for a symmetric attentional curve (outcome 2). Instead this could mean that the attentional curve is so strongly peaked that it already reached zero at phase 1/4 and -4/3. (Phase -4/3 == phase 3/4 because of periodicity)

Experiment 2: Tapping behaviour

This experiment will shine a light on the other side of beat induction: the motor synchronization. The previous experiment was on perceptual sensitivity, which takes place in the higher brain regions, while this experiment is on finger tap synchronization, a task that might bypass these high brain regions.

For each trial, participants are presented an isochronous set of beeps in a comfortable tapping rate, to which they have to synchronize their finger taps. When synchronization is successful, the external input will cease, but participants are asked to continue tapping. The last inter-onset-interval (IOI) before the silence can be varied by the experimenter with a delta t from -1/2 period to +1/2 period. From the inter-tap-interval (ITIs) after the last onset, the amount of phase adjustment of the internal timekeeper can be calculated. This is the tapping-equivalent of the sensitivity curve in experiment 1. From the following ITIs we are also able to calculate a possible change in internal tempo induced by a single IOI deviation. For each value of the final ITI, multiple trials are needed to reduce measurement uncertainty.

The curve that results from this experiment is not necessarily the same as that of conscious perception in experiment 1. Also, we are able to take more measuring points, since we are only limited by the number of desired trials when probing the phase interval [-0.5, 0.5].

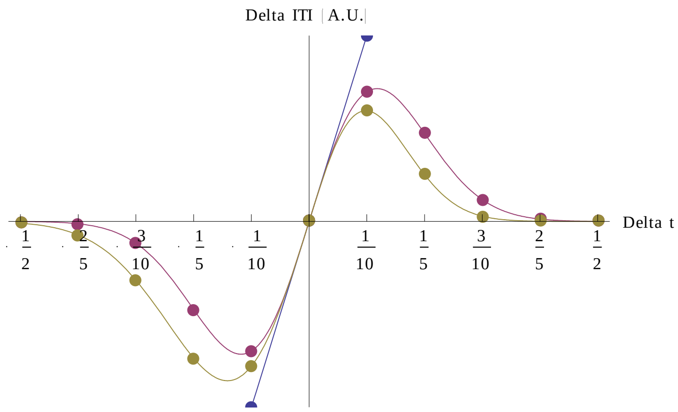

Fig 3 Phase adjustment due to a change of IOI with size delta t. The difference of the tap interval after the perturbation with the average tap interval is the phase adjustment of the internal timekeeper. The phase adjustment is plotted here for some values of delta t. In principle the phase adjustment can be measured for any value of delta t, the dots are only examples. Delta t is expressed in fractions of the period here.

In this experiment, we also expect to find a modulation of phase adjustment for different measuring positions (Repp 2002a, 2002b). Considering the correlation between the thresholds for awareness of tempo change and adjustment of the internal oscillator’s period (Repp, 2001), we expect that the tempo of the internal timekeeper would only be affected at large delta-t and not for small. From Repp (2003) we expect to see an asymmetry in phase correction for “too early” and “too late” pulses will also show up in this experiment. Eck’s model also predicts this asymmetry here: earlier onsets will have more impact than later onsets.

I want to point out once more that both experiments investigate a similar property of beat induction: inter-beat (in)sensitivity. There is an important difference however: The first experiment is a perceptual task, while the second acts on the level of motor synchronization. Their correspondence is not trivial: In literature (Kubovy & Van Valkenburg, 2001), completely separated auditory pathways of neural processing for perception and action have been discussed. As will become evident further on, differences and similarities in the experimental results might help when constructing different parts of the model.

PHASE II: Simulations

In this phase we want to study literature and do more simulations to find more discrepancies between Eck's model and experimental data. An already known shortcoming of Eck's model is that it shows no period adaptation. However, it can make a phase adjustment every period, making it look like the internal period has changed. Only, this solution is not satisfying: when the external input ceases, the period of the Eck model will fall back to its preferred tempo. This is in contrast to measurements from Semjen et al. (2000) that show that people will continue tapping in the last heard tempo. One of the other possible differences between literature and simulations on Eck's model can be that the model takes longer to synchronize. From tapping data (Fraisse, 1966), it is known that about three beats are enough to synchronize, while figure 2 in Eck 2002 implicitly suggests that synchronization might take up more than 10 beats. To quantify this suggestion a new simulation is necessary.

We will expand the model of Eck to resolve the found anomalies. Therefore we want to investigate the behavior of multiple coupled oscillators. Eck proposed that this might improve performance on syncopated beats. Moreover, we expect that such a network might decrease synchronization time. This is because an oscillator that was, due to different random starting parameters, closer to synchronization can synchronize faster and dominate other unsynchronized oscillators. Next we want to solve the lack of period correction by extending the network with extra cells that can modulate the synaptic connections in Eck's oscillator in order to change its intrinsic period. In the next paragraphs I will shortly sum up some research on beat induction that will give support with the formation of the model.

In studies by Repp (2002a, 2002b) an isochronous stimulus was perturbed with such a small amount that the participants did not notice the perturbation. They were asked to tap along with the stimulus. Their tapping behaviour did respond to the perturbations, and did follow the adjusted onset positions. At the moment of adjustment, extra fMRI activity was measured in the cerebellum. The results of this experiment can be fully explained by Eck's oscillator. The cerebellum is associated with body movement planning (Gazzaniga et al., 1998). Also, Repp & Keller (2004) showed that phase correction was not disturbed by attention distractive tasks. Furthermore an fMRI study showed cerebellar activity at the time of phase correction (Lutz et al., 2000These are clues that Eck's network would be found in the cerebellum. The lack of period correction in this small network is consistent with Praamstra et al. (2003) who found that period and phase correction are neurally dissociated.

Repp (2001) showed that period adjustment only takes place at values of *delta t* that can be consciously perceived. So there is no unconscious period adjustment; it only takes place above a certain threshold where the difference in tempo is noticeable.

At the moment of period correction, extra brain regions become active under fMRI observation: Stephan et al. (2002) showed increased activity in the prefrontal cortex (PFC) , associated with conscious supervision of behaviour (Shallice, 1982, 1988). Grahn (2009) found clues that the basal ganglia are involved, particularly for rhythms with weak metric structures.

Between the cerebellum and the prefrontal cortex and basal ganglia are found specialized loops (Middleton & Strick, 2000; Habas et al., 2009; O'Reily et al., 2010; Hoshi et al., 2005). Signals from these loops can change the synaptic strengths of Eck's oscillator network, changing its intrinsic period. The basal ganglia are already associated with sensory motor synchronisation (Schwarze et al., 2010). Therefore these loops will be the first subject of study regarding the signalling of period adjustment. Literature study is needed on how the error signal from the cortex exactly modulates the synaptic connections.

An important finding in the literature referred to above is the separation between phase correction and period correction. These are completely independent and probably spatially separated areas, one coupled to conscious perception, and the other unconscious.

In conclusion: A lot of experimental data and new insights on cerebellar communication are present in literature, which not have been brought together yet. In phase 2, we want to use this information to construct a model that has a strong neural analogy, and also predicts the position of its components.

PHASE III: Anatomical verification

Phase 3 will involve verifying the anatomical positions of the model. If indeed a network is constructed predicting that certain functions take place in the cerebellum and other in a part of the cerebral cortex or basal ganglia, we will use fMRI and TMS to verify these locations. Koch et al. (2009) provides a useful review of TMS experiments concerning time processing.

We will investigate whether participants would consciously perceive period changes in an external stimulus when the synchronization oscillator in the cerebellum is switched off or highly distorted using TMS, as well as the opposite: What happens to period correction when a part of (the communication with) the counterparting brain region is disrupted?

PHASE IV: Model construction

In this final phase we will adjust the model to incorporate the findings in the experiments in phase 3 and be the first one to propose a model for beat induction, together with its neural correlate. This model will be a computational oscillator model, giving a qualitative description of beat induction. For a quantitative model a realistic deduction for all model parameters is required. This is a suggestion for subsequent research.

6b Application perspective

Rhythmic auditory stimulation has proven to be useful in treating patients with Parkinson's disease (McIntosh et al., 1997; Thaut et al., 2007) and apraxia of speech (Shane & Darley, 1978). Further research of the internal processing of these stimuli will open doors to creating more purpose directed stimuli.

Furthermore, the Fitzhugh-Nagumo model has been used extensively in research on attention and synchronicity and specialization of small networks in the brain (some examples: Peng et al., 2008; Stefanescu et al., 2008; Wang et al., 2010) Understanding and mastering such networks and their mutual interactions can, next to useful knowledge on the research topic, also give new information and inspiration for these other fields of brain research.

7 project planning

Year1 / phase I
Further orientation / Literature Study
Experiment 1: Attentional focus
Experiment 2: Tapping behaviour
Publication experiments: Peer reviewed journal

Year2 / phase II
More simulations model Eck
Searching literature for discrepancies with model
Working on a neurally plausible model
Publication of the model in peer reviewed journal

Year3 / phase III
Experiment 3: Testing the model on brain with fMRI / TMS

Year4 / phase IV
Rewriting model
Integration & synthesis
Writing PhD thesis

8 Expected use of instrumentation
No new instrumentation is needed. Access to existing fMRI and TMS equipment is necessary in phase 3.

9a Literature research team
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10 Requested budget

(1) PhD Student